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Consistent Performance Differences Despite Manipulation of Cue Switching Variables in Children and Adults

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Consistent Performance Differences Despite Manipulation of Cue Switching Variables in Children and Adults

by

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Dedication

To my mother and future husband.

Acknowledgements

I would like to thank my adviser, Dr. Jessica Church-Lang, for helping me bring this thesis to life. While working with Dr. Church I gained invaluable experience and was able to share this work with my peers and members of the scientific community at several conferences. Through all the struggles, breakthroughs, long days and nights, Dr. Church was a source of motivation and ideas. For this and more, I thank Dr. Church. Further, this project would not have been possible without the help and dedication from members of the Church Lab and funding from University of Teas at Austin. I would me remiss if I did not thank my mother, fiancé and close friends for keeping me sane, grounded and smiling throughout this process. And finally, I would like to thank all of the parents, children, undergraduates and adults who participated in this study.

Abstract

Consistent Performance Differences Despite Manipulation of Cue Switching Variables in Children and Adults

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To compare the stability of task-switching abilities across children and adults, we created a task with four goals in mind. First, we aimed to test whether certain task manipulations would reduce differences in adult and child performance. We created a nine level switching task, with changes in response choice consistency, number of response choices, and number of cued tasks. Second, we wanted to assess possible performance transitions within the child age group. We did this by subdividing the child group into smaller age bins. Third, we aimed to measure any short-term improvement across the study session. To do so, we compared responses from the first level of the task to an identically formatted level 10. Finally, we created a second study to investigate the effects of a higher working memory demand With respect to our first goal, attempts to reduce differences in adult and child performance were largely unsuccessful; children were consistently slower, less accurate, and more affected by task-level manipulations than adults. Our performance assessment within the child group identified a transition where participants as young as 12 years in Experiment 1 and 14 years in Experiment 2 displayed more adult-like responses in response times. In both studies, as the child age increased, we observed gradual improvement in accuracy. Regarding our third goal, we found similar amounts of improvement in both response time and accuracy for both adult and child groups, despite the high starting level of performance in adults in both studies.

Added cognitive demand in Experiment 2 promoted significantly more improvement in both age groups. Thus, these novel tasks temporarily improved task-switching abilities in children and adults within a single session. As a whole, these results reveal consistent differences in task switching performance between age groups, but also relative flexibility (in the short-term) within a given individual.

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INTRODUCTION

Chapter 1: Literature Review

WHAT IS COGNITIVE FLEXIBILITY?

In the context of this study, we define cognitive flexibility as the ability to adjust to new tasks and demands. This skill emerges relatively late in development, subsequent to other control processes such as inhibitory control, response inhibition and working memory [Diamond, 2013; Rueda, Posner & Rothbart, 2005; Braver, Reynolds & Donaldson, 2003; Allport, Styles & Hsieh, 1994; Rogers & Monsell, 1995; Luna et al., 2010; Cepeda et al., 2001; Kiesel et al., 2010]. Similarly, the ability to maintain items in working memory increases throughout late adolescence, providing further evidence for the prolonged development of the ability to adapt to and maintain multiple tasks [Diamond, 2002; Braver, Reynolds & Donaldson, 2003; Rubia at al., 2006; Luna et al., 2004; Kray, Eber & Lindenberger, 2004]. The literature on cognitive flexibility and working memory is vast, and most notably studied using task-switch paradigms [Meiran, 1996; Allport, Styles & Hsieh, 1884; Rodgers & Monsell, 1995; Braverman & Meiran, 2010; Forrest, Monsell & McLaren, 2014; Kiesel et al., 2010; Luna et al., 2010; Koch et al., 2010] and conflict tasks such as the Attention Network Test (ANT) [Rueda et al., 2004; Rueda, Posner & Rothbart, 2005]. In task switch paradigms, a participant is cued to respond using varying rules on a trial-by-trial basis [Meiran, 1996; Kiesel et al., 2010; Rodgers & Monsell 1995; Monsell, 2003]. For example, in a design where stimuli are colored shapes, one trial may require participants to match a target and a response choice based on color, while another trial may require matching the target based on shape [Zanolie et al., 2008; Casey et al., 2004]. Other methods include categorizing words or images, comparing values of digits, or sorting by direction (up/down vs. right/left) [Gade

& Koch, 2007; Braverman & Meiran, 2010; Rueda et al., 2004; Lui et al., 2011; Bunge & Wendelken, 2009].

In all instances, task-switch paradigms entail keeping tasks in mind, responding according to the critical task rule, maintaining attention and inhibiting incorrect responses on a trial-by-trial basis. These paradigms allow us to measure cognitive control by monitoring response times, accuracy, and switch-costs, or the increase in response time and errors made during trials that require use of a different task-set than the preceding trial [Braver, Reynolds & Donaldson, 2003; Monsell, 2003; Koch et al., 2010; Gade & Koch, 2007; Meiran et al., 1996; Rodgers & Monsell, 1995].

DEVELOPMENTAL DIFFERENCES IN TASK-SWITCHING

Effortful control slowly emerges in early childhood [Rueda, Posner & Rothbart 2005; Kochanska, Murray, & Harlan, 2000]. Many studies have demonstrated that task-switching ability, measured by both response time and accuracy, improves through development [Cepeda et al., 2001; Kray et al., 2004]. Switch-costs, or decrements in performance due to task or rule changing, are larger in younger children. Younger participants also have greater difficulty in conditions with inconsistently mapped responses due to perseveration on previous rules, more than one possible task (mixed blocks), and conditions with a higher cognitive and working memory load [Cepeda et al., 2001; Los, 1996; Crone et al., 2006; Gade & Koch, 2007; Mayr & Kliegl, 2000]. Luna and colleagues remind us that these performance improvements post-adolescence are not strictly due to pubertal changes; instead, complex factors such as genetics, socioeconomic status and stress levels are at play [Luna et al., 2010].

Previous work in behavioral and neuroimaging fields have found differences in the developmental timing of certain aspects of cognitive control such as task-set reconfiguration, rule representation and set-switching [e.g. Crone et al., 2006; Bunge & Wright, 2007]. Previous studies also suggest adult levels of switching performance can be attained around 12 years of age [Luna and Sweeney, 2004; Cepeda et al., 2001; Bunge et al., 2002]. While developmental trajectories of certain sub-components of task switching have been explicated [Zanolie et al., 2008; Rueda, Posner & Rothbart, 2005; Reimers & Maylor, 2005], finer age distinctions and exploration of performance transitions remain of interest.

For instance, evidence of functional working memory has been observed in infants as young as 9-12 months old, while self-control develops later in adolescence. Previous work has demonstrated the inherent difficulty in determining how different aspects of task-switching change across age and how these components work together to affect overall performance [Rueda, Posner & Rothbart, 2005; Fan et al., 2005]. Certain components of executive function are difficult to disentangle. For instance, working memory supports response inhibition and visa versa. Diamond outlines a still present debate regarding whether inhibitory control can be isolated from working memory [Diamond, 2013]. In this study, we aimed to examine the differences and similarities in performance across a broad age range to capture developmental shifts in detail.

THE CURRENT STUDY

To assess the development of different aspects of task-switching abilities, we compared task-switching performance of typically developing children ages 6 to 16 years to that of UT-affiliated young adults ages 18 to 27 years.

Several manipulations were tested: number of cued tasks, number of response choices (which corresponded to the number of response buttons), and response choice consistency from trial to trial. We assessed task switch-costs by measuring differences in performance between when a trial repeated the task from the previous trial to when the task differed between consecutive trials. We captured response switch-costs by measuring differences in performance between trials in which the required button response alternated relative to the preceding trial in comparison to trials in which the same button response was required [Meiran, 2000; Crone et al., 2006].

As a between-subjects manipulation, we created three congruency condition subgroups varying the proportions of an exact match between the target and the correct response stimuli from 0% of the time, to 20% or 40% [Meiran & Kessler, 2008; Egner, 2007; Mayr & Kliegl, 2000; Meiran, 2000; Wendt et al., 2008; Kiesel, Wendt, & Peters, 2007].

Specifically, our goals for Experiment 1 were threefold: First, we aimed to discover whether any task-switching manipulation resulted in greater overlap of child and young adult performance, either by degrading adult performance, or enhancing child performance. Greater task performance overlap would be useful for neuroimaging, where performance confounds create difficulties in interpreting developmental differences [Church et al., 2010]. Second, we wanted to assess if there were any clear age transitions in task-switching performance. Finally, we wanted to assess our ability to improve task performance through short-term learning (within the test session) by comparing the first level of the task and an identical level (level 10) at the end of the experiment.

Based on preliminary results from Experiment 1 revealing consistent ceiling performance levels in adults, we aimed to create a more difficult task. Our goal in Experiment 2 was to create a similar task with an increased cognitive load via an increased working memory demand. Further, we wanted to investigate the three overall goals posed in Experienced 1 in Experiment 2 as well.

Chapter 2: Research Questions and Hypotheses

RESEARCH QUESTION 1:

Which manipulations will affect child and adult performance within the task? And can we target certain aspects of task control systems so child and adult performance will be more similar?

Hypothesis 1

In this study we aimed to test the effects of several cue-switching manipulations across development. We created three congruency condition groups (0%, 20%, 40%) as a between subjects measure in both age groups. We also added within-subject manipulations of task repeating/switching ("task-switching"), level and number of response choices. We hypothesized task performance (as measured by response time and accuracy) would decline even for adults in later levels, and thus there might be points at which adult performance would be more similar to child performance. By manipulating global between- and within-subject factors, we aimed to tease apart which factors strongly influence task-switching behavior.

RESEARCH QUESTION 2:

Are there clear developmental transitions in task-switching performance?

Hypothesis 2

Based on previous findings that have observed shifts in performance after the age of 12 [Rubia et al., 2006; Luna et al., 2010], we hypothesized we would find a transition in performance around at a similar time point in the child group. We define a shift in performance by a significant difference in accuracy or response time between older children and their younger peers. We hypothesized children with more adult-like performance would be more robust to manipulations in the later, more difficult levels with four response choices. We had no specific hypotheses about gender; however, we anticipated female children might have slightly higher performance than their same age male peers based on previous findings indicating earlier pubertal anatomical and structural brain changes in females which can be reflected in earlier development of executive functions [Blakemore & Choudhury, 2006]

RESEARCH QUESTION 3:

Will we see short-term learning within a test session?

Hypothesis 3

Short-term improvement within the task in the child group would serve as a proxy to measure the degree to which cognitive flexibility can be trained or improved in children. We hypothesized that by designing the task to become increasingly more difficult across each level as more manipulations, short-term learning would be facilitated in children after nine levels of challenge and practice.

RESEARCH QUESTION 4:

How does working memory load interact with task-switching performance over age?

Hypothesis 4

Based on the principle that cognitive processing limits are more likely to be exceeded when cognitive load increases, introducing a higher working memory component into a second experiment should significantly lower performance across in both age groups. More specifically, we expected adult performance to decline from ceiling levels, allowing a more comparable analysis alongside the child age group. We also hypothesized task-switch costs should globally increase in the high working demand experiment (Experiment 2) relative to the low working memory demand experiment (Experiment 1).

METHODOLOGY

Chapter 3: Experiment 1

PARTICIPANTS:

Behavioral data was collected from 60 children aged 6-16 years (M = 11.36 years, SD = 2.59, 30 female) and 60 young adults aged 18-27 years (M = 20.33 years, SD = 2.09, 30 female). Children were recruited through schools in the greater Austin area, through the Children's Research Lab database at UT Austin, and through external outreach and recruiting events. Young adults were recruited from the University of Texas at Austin through flyers, online postings and PSY301 (Introduction to Psychology), where students received class credit for their participation. Children and young adults who were not enrolled in PSY301 received $10 compensation. All participants reported to be in good health, were not taking any psychiatric medications, and had normal or corrected-to-normal vision. We had no hypotheses regarding handedness (10 adults and 19 children were left handed). Participants were matched on age and gender in both adult and child age groups in each between-subject experimental condition (0%, 20% or 40% congruency; see task details below).

One child did not complete level 10, two children did not complete levels eight and nine, and one child did not complete level nine. These children were included in the analysis. However, an additional 12 adults (3m/9f, M= 19.7 years, SD = 1.98) and 13 children (8m/7f, M = 9.8 years, SD = 2.37) beyond the 120 described above were excluded from the analyses due to computer errors, incomplete data sets, or failure to meet eligibility requirements. Of the 25 unincluded participants, five participants were excluded from analysis specifically because their performance was more than 2.5

standard deviations from the mean on four or more of the 10 task levels for either response time or accuracy.

The International Review Board (IRB) at the University of Texas at Austin approved all materials and task procedures involve. Children provided informed assent and were accompanied by a parent who also provided informed consent before participation. Young adults provided informed consent before participation as well. All IRB protocols were followed, with emphasis on informed consent, potential risks and benefits of participating as well as freedom to decline participation before or during the study.

STIMULI, MATERIALS, TASK:

The experiment was created and executed on an Apple laptop (MacBookPro), using PsychoPy Toolbox [Brainard, 1997; Pelli, 1997; Kleiner et al., 2007] and R Studio [R Core Team, 2015] and a USB hand-held button box (Delcom Products). There were four possible task rules to follow: matching by shape, inner color, pattern, or outer color. The task for a given trial was cued on a task indicator bar with a red outline. Stimuli consisted of red, green, orange, and blue colored squares, hearts, diamonds and circles. The four patterns were zigzag, polka dot, cross and grid patterns with either red, green, orange, and blue outer color borders.

Each time a target appeared on the screen, participants were instructed to match the target (bottom row) to the best response choice (second row) based on the task rule, which was highlighted in a red outline in the task indicator row (top row) (see Figure 1). Subjects responded by using a hand-held button box where each button corresponded to a response choice on the screen. Response mappings remained on the screen when the target appeared and throughout the experiment to reduce difficulty.

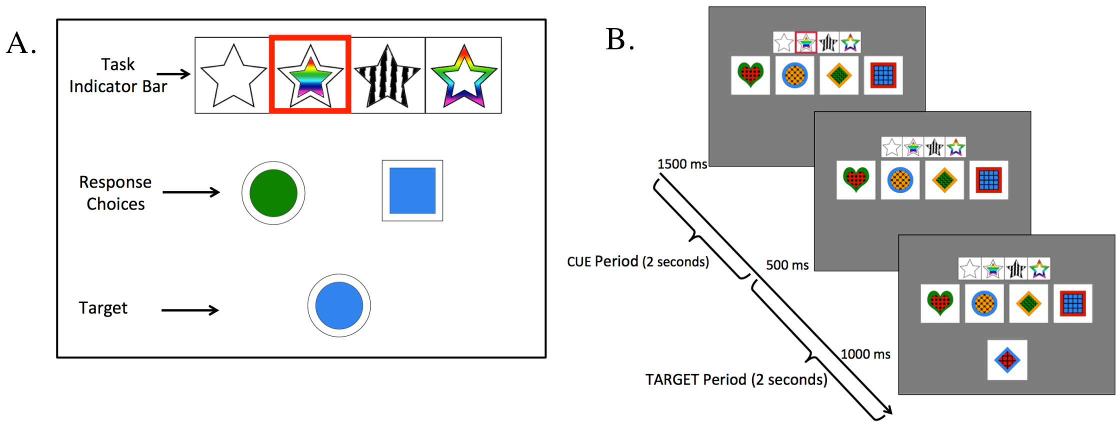

Figure 1 | (A) Underlying task structure. The task indicator bar cued 2, 3, or 4 possible rules during each level. Participants matched a target to a response choice based on shape, inner color, pattern, or outer color. The stimuli pictured above are from level 1, which had cues for shape and inner color only and two response choices. **(B)** Example of stimulus display in a four button and four feature level. The first row, the task indicator bar, shows the four possible rules: shape, inner color, pattern and outer color. All four rules are possible cues in this example. The cue (task rule indicated by a red outline) was presented for 1500 ms. The target appeared after a 500 ms delay for 2000 ms. Participants were required to indicate a response by selecting a button on the button box before the end of the trial (4000 ms total).

The task involved four main manipulations, one between-subject, and three within-subject. The between-subject manipulation was Congruency: a manipulation of how often the target exactly matched a response choice (0%, 20%, or 40% of the time). The three within-subject manipulations were (1) Trial Type: whether the task switches or repeats from trial to trial, (2). Level: the task became incrementally more difficult by combining and adding different manipulations across 9 separate levels or runs. The third within-subject manipulation was (3) Number of Response Choices: whether a task level had two or four response choices mapped on to either two or four buttons, respectively.

PROCEDURE:

Participants were instructed that the task was a matching game during which they were to match a target to the correct response choice based on different features (see Figure 1). Participants were told to respond as quickly and as accurately as possible. Each trial began with the task indicator row (with the task cue outlined in red) and the response choices on the screen for 1500 ms. The red cue box disappeared from the top row after 500 ms, and then the target appeared for 2000 ms. The task indicator row and the response choices remained on the screen throughout the trial (total trial length: 4000 ms) (see Figure 1).

A practice level of 25 trials was presented, during which the stimuli remained until the participant responded rather than after a fixed time limit. The practice level shifted between 2 task features and had 2 response choices that were consistent throughout the run. The actual experiment consisted of 10 levels. Levels one, two and ten consisted of 25 trials, level three included 31 trials, and levels four, five, six, seven, eight and nine consisted of 53 trials. Thus in total, each complete data set for one subject consisted of 424 trials and 25 practice trials. A breakdown of each level is pictured in Table 1. All participants were tested individually in a testing room or a quiet lab space. The experimental visit lasted approximately one-hour including consenting, study-related questions, instructions, practice, and the experiment.

Table 1. | Layout of Within-Subject Between-Level Manipulations. Levels varied in difficulty via manipulations of the number of possible cued tasks, number of response choices and consistency of the response choices mapped on the screen.

	Within-Subject Manipulations		
Level	Number of Tasks	Number of Response Choices	Mapping Consistency
Level 1	2	2	Consistent
Level 2	2	2	Mixed
Level 3	3	2	Consistent
Level 4	4	2	Consistent
Level 5	4	2	Mixed
Level 6	4	2	Inconsistent
Level 7	4	4	Consistent
Level 8	4	4	Mixed
Level 9	4	4	Inconsistent
Level 10	2	2	Consistent

Chapter 4: Experiment 2

PARTICIPANTS:

Behavioral data was collected from 47 children aged 6-16 years (M = 11.22, SD = 2.12, 21 female) and 48 young adults aged 18-25 years (M = 20.2, SD = 1.73, 26 female). Children were recruited by contacting schools in the greater Austin area, utilizing a database of past participants at the Children's Research Labs at UT Austin and through external outreach and recruiting events. Young adults were recruited from the University of Texas at Austin through flyers, online postings and PSY301 (Introduction to Psychology), where students received class credit for their participation. Children and young adults who were not enrolled in PSY301 received $10 compensation. All participants reported to be in good health, not taking any psychiatric medications, and having normal or corrected-to-normal vision. We had no hypotheses regarding handedness (3 adults and 7 children were left handed). Participants were matched on age and gender in both adult and child age groups in each experimental condition (0%, 20% or 40% congruency; see task below).

Two children did not complete levels eight and nine, and three children did not finish level nine. These children were included in the analysis. However, an additional 12 adults (7m/5f, M= 19.38 years, SD = 1.016) and 7 children (2m/5f, M = 8.86 years, SD = 1.608) were excluded from the analyses due to computer errors, incomplete data sets or failure to meet eligibility requirements. Of the 19 total removed participants, four participants were excluded from analysis specifically because their performance was more than 2.5 standard deviations from the mean on four or more levels (for either response time or accuracy).

The International Review Board (IRB) at the University of Texas at Austin approved all materials and task procedures involve. Children provided informed assent and were accompanied by a parent who also provided informed consent before participation. Young adults provided informed consent before participation as well. All IRB protocols were followed, with emphasis on informed consent, potential risks and benefits of participating as well as freedom to decline participation before or during the study.

STIMULI, MATERIALS, TASK:

The experiment was created and executed on an Apple laptop (MacBookPro), using PsychoPy Toolbox [Brainard, 1997; Pelli, 1997; Kleiner et al, 2007] and R Studio [R Core Team, 2015], and a USB hand-held button box (Delcom Products). There were four possible task rules to follow: matching by shape, inner color, pattern, or outer color. The task for a given trial was cued on a task indicator bar with a red outline. Stimuli consisted of red, green, orange, and blue colored squares, hearts, diamonds and circles. The four patterns were zigzag, polka dot, cross and grid patterns with either red, green, orange, and blue outer color borders.

Each time a target appeared on the screen, participants were instructed to match the target (bottom row) to the best response choice (second row) based on the task rule, which was highlighted in a red outline in the task indicator row (top row) (see Figure 1A). Subjects responded by using a hand-held button box where each button corresponded to a response choice on the screen. Response mappings remained on the screen when the target appeared and throughout the experiment to reduce difficulty.

The task involved four main manipulations, one between-subject, and three within-subject. The between-subject manipulation was Congruency: a manipulation of how often the target exactly matched a response choice (0%, 20%, or 40% of the time). The three within-subject manipulations were (1) Trial Type: whether the task switches or repeats from trial to trial, (2). Level: the task became incrementally more difficult by combining and adding different manipulations across 9 separate levels or runs. The third within-subject manipulation was (3) Number of Response Choices: whether a task level had two or four response choices mapped on to either two or four buttons, respectively.

PROCEDURE:

Participants were instructed that the task was a matching game during which they were to match a target to the correct response choice based on different features (see Figure 2). Participants were told to respond as quickly and as accurately as possible. Each trial began with the task indicator row (with the task cue outlined in red) and the response choices on the screen for 1500 ms. The task cue then disappeared from the top row, and after a 500 ms delay the target appeared for 2000 ms. The blank task indicator row and the response choices were not on the screen during the last 1000 ms of the trial (see Figure 2).

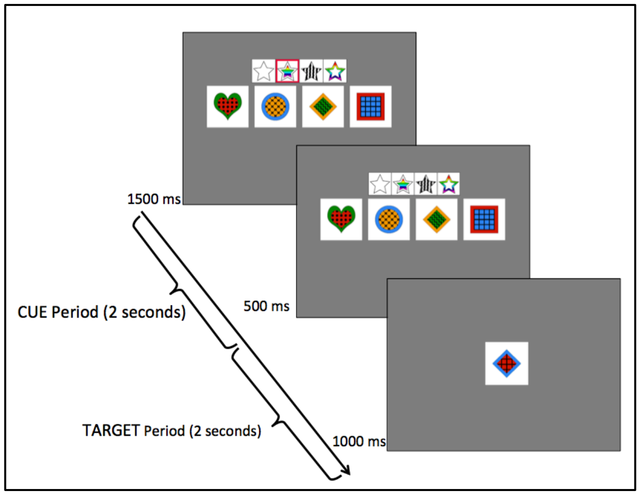

Figure 2 | Example of Stimulus Display in Experiment 2. The first row, the task indicator bar, shows the four possible rules: shape, inner color, pattern and outer color. All four rules were possible cues in this example. The cue (task rule indicated by a red outline) was presented for 1500 ms. The target appeared after a 500 ms delay for 2000 ms. Participants were required to indicate a response by selecting a button on the button box before the end of the trial (4000 ms total). The above frame is from a level with four features/rules (i.e. levels 7, 8, and 9).

A practice level of 25 trials was presented, during which the stimuli remained until the participant responded rather than after a fixed time limit. The practice level shifted between 2 task features and had 2 response choices that were consistent throughout the run. The actual experiment consisted of 10 levels. Levels one, two and ten consisted of 25 trials, level three included 31 trials, and levels four, five, six, seven, eight and nine consisted of 53 trials. Thus in total, each complete data set for one subject consisted of 424 trials and 25 practice trials. All participants were tested individually in a testing room or a quiet lab space. The experimental visit lasted approximately one-hour including consenting, study-related questions, instructions, practice, and the experiment.

Chapter 5: Data Analysis Methods

All analyses were conducted using R Studio [R Core Team, 2014]. **Hypothesis 1:** To test which manipulations affected child and adult performance within the tasks, we used a repeated measures linear mixed effects regression with a $3 \times 2 \times 10 \times 2$ factorial design. The model included between-subject manipulations of congruency condition (3) and age group (2), and within-subject manipulations of level (10) and task repeating/switching ("task-switching") (2).

We used a repeated measures linear mixed effect model design using maximum-likelihood estimation. Linear regression allows flexibility when analyzing unbalanced data sets and also accounts for unique structures of data collection. We started with the full model with all possible interactions for both response time and accuracy. We derived the final models using backward elimination [Pinheiro & Bates, 2000]. In this procedure, the highest-level non-significant interaction is removed to determine whether it significantly contributes to the variance. Non-significant factors are removed, and significant factors are kept in the model. Both final models had lower Akaike information criterions (AIC) values than their respective full model suggesting they were more parsimonious than the starting full models [Pinheiro & Bates, 2000]. Results reported from these analyses were generated from an analogue ANOVA using the anova() command in R Studio. In addition to the linear regression model, we investigated the effect of number of response choices (corresponding to number of response buttons) using post-hoc paired t-tests.

Hypothesis 2: In order to investigate if there were any clear developmental transitions in performance related to task-switch manipulations, we conducted post hoc t-tests between the young adult and child group and within the child age group. This second analysis was conducted for both response time and accuracy data. **Hypothesis 3:** Finally, we tested if there was any short-term learning within the task using post-hoc t-tests. The analyses were conducted within the two age groups by comparing performance in the first level 1 and the last level 10 of the experiment session using post-hoc t-tests in Experiment 1. **Hypothesis 4:** For consistency of results, we used the same full starting model and backward elimination procedures in Experiment 2 as we did for Hypothesis 1 in Experiment 1.

RESULTS

Chapter 6: Experiment 1

CHILDREN WERE LESS ACCURATE AND SLOWER THAN ADULTS

Accuracy

The task accuracy analysis revealed main effects of age, $F(1,116) = 91.73$, $p < .0001$, level, $F(9,4581) = 45.26$, $p < .0001$, and task-switching, $F(9,4581) = 51.24$, $p < .0001$. Contrary to our hypotheses, there were no significant differences between congruency conditions overall, $F(2,116) = .48$, $p > .6$, or in interaction with age (Age x Congruency) $F(2,114) = .65$, $p > .5$. The following results in this chapter are thus collapsed across the congruency condition groups.

Overall, children were less accurate than adults on the task, (M = 73.51%, SD = 17.63 vs. M = 91.9%, SD= 6.74). As expected, a significant main effect of task-switching revealed switch trials were less accurate relative to repeat trials (see Figure 4). The average switch cost in accuracy for young adults and children was 2.1%, 3.3%, respectively. A two-way interaction between age and task-switching, $F(1,4542) = 6.81$, $p < .01$, showed switch costs occurred similarly in both young adults and child age groups.

Child accuracy significantly differed between the two and four response choice levels by 15% (M = 78.17, SD = 12.39, in two choice levels, M = 63.17, SD = 20.06, in four choice levels) $t(98.29) = 4.93$, $p < .0001$. Adult accuracy was also significantly different between response number conditions by about 3% (M = 93.15, SD = 4.07, in two choice levels, M = 90.08, SD = 6.11, in four choice levels) $t(102.69) = 3.23$, $p < .01$ (see Figure 3).

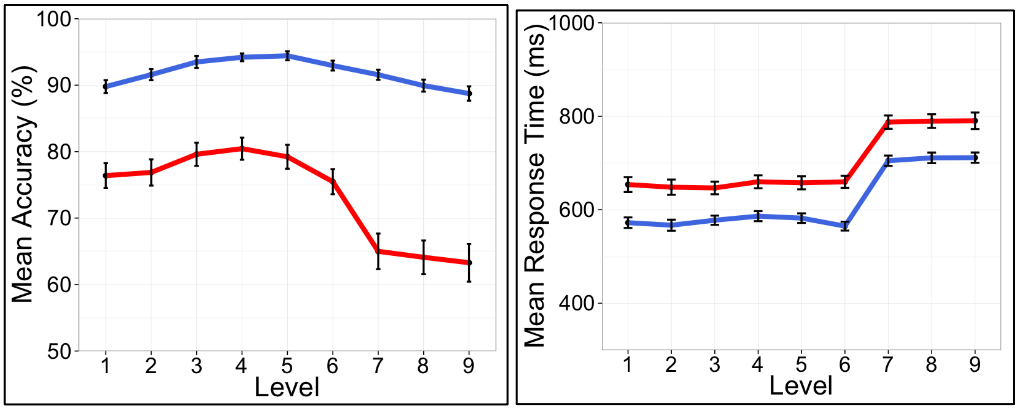

Figure 3 | Overall Performance Across Levels in Experiment 1. Accuracy had a significant interaction between age and level ($p < .0001$), with children (red) showing a greater decrement in accuracy than adults (blue) at the higher levels. Response times had no interaction between age and level ($p > .5$); performance for both groups slowed with the switch from two to four response choices at level 7.

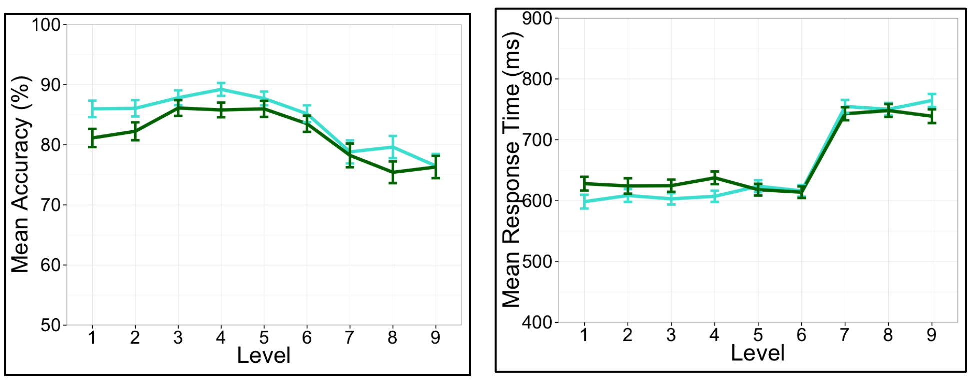

Figure 4 | Overall Task-Switching Performance in Experiment 1. There was a significant two-way interaction between task switching and level manipulations for accuracy ($p < .001$) and response times ($p < .0001$). There was no significant interaction between age, task switching, and level ($p > .2$) in either response times or accuracy.

Response Times

The response time regression analysis revealed main effects of age, $F(1,116) = 26.02$, $p < .0001$, level, $F(9,4563) = 273.85$, $p < .0001$ and task-switching, $F(1,4563) = 10.95$, $p < .001$. Again, there were no significant differences between congruency conditions overall, $F(2,116) = .878$, $p > .4$ or between the age groups (Age x Congruency) $F(2,114) = .517$, $p > .5$.

There was no significant interaction between age and level, $F(9,4524) = .88$, $p > .5$; children were consistently slower than young adults throughout the game. Children's response times significantly differed between two (M = 653.75, SD = 97.07) and four 792.11, SD = 110.35) response choice levels by 138.36, $t(116.2) = 7.28$, $p < .0001$. Adult response times were also significantly different between the response number conditions by 134.45 ms (M = 575.09, SD = 73.49 in two choice levels, M = 709.54, SD = 79.25 in four choice levels) $t(117.34) = 9.64$, $p < .0001$ (see Figure 3).

Overall, response times were significantly slower in switch trials (M = 664.42, SD= 129.19) relative to repeat trials (M = 657.37, SD= 130.32). There was a significant two-way interaction between task-switching and level manipulations for response times, $F(9,4524) = 5.74$, $p < .0001$. Repeat trials were faster than switch trials overall in levels 1 through 4, yet surprisingly, repeat trials were slower or equal to switch trials in levels 5-8, $t(1663.98) = .099$, $p > .9$, indicating a small task cue repeat cost when there were four button choices.

TRANSITION TO ADULT-LIKE PERFORMANCE LEVELS WAS OBSERVED AT 12 YEARS

We binned the child age group by chronological age-year in order to investigate performance changes over age in more detail from ages 8 to 15 years. Post-hoc paired comparisons revealed that beginning at the age of 12; children begin to show adult-like response time performance $t(79.12)= 1.5$, $p > .1$. Interestingly, the similarity between adult and 12-year-old performance grew more pronounced in later levels with four response choices and an increased cognitive load (levels 7, 8 and 9), $t(27.58)= 0.9$, $p > .3$.

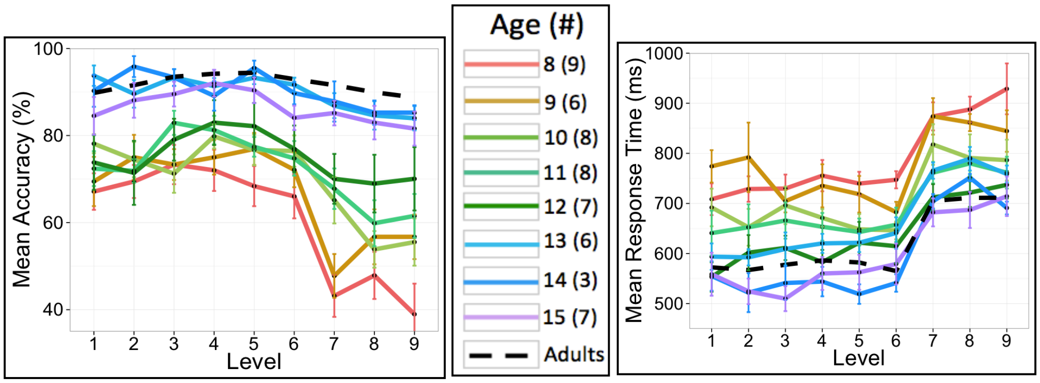

Figure 5 | Age Transition in Experiment 1. Children ages 12-15 performed significantly better than younger participants (p < .0001) in both accuracy and response time and demonstrated more adult-like patterns of performance. Post-hoc t-tests revealed a transition from child-like levels of response times starting around the age of 12 years (p > .1).

Post-hoc t-tests demonstrated as a group, children ages 12-15 years also performed significantly more accurately $t(513.37) = 14.26$, $p < .0001$, and faster than their younger peers, $t(485.52) = 12.01$, $p < .0001$ (see Figure 5). Importantly, almost all older child age bin group response times were not significantly different from adult performance (P-value by age year: 12: $p > .1$, 13: $p < .01$, 14: $p > .2$, 15: $p > .1$).

Temporary Learning Within Task

More young adult and child participants improved their response time performance within the experiment session. Overall, 88 of the 119 participants who completed both levels 1 and 10 (68% children; 80% adults) improved in response time. Roughly half the participants 64 out of 119 (53% children; 55% adults) improved in terms of accuracy. We found similar amounts of behavioral improvement for both age groups, despite high starting levels of performance in adults. Additional post hoc t-tests were conducted to investigate learning from the first level to an identical level (with different stimuli) at the end of the study (level 10). Both children and young adults improved their performance over the course of the experiment (approximately 45 minutes) (see Figure 6).

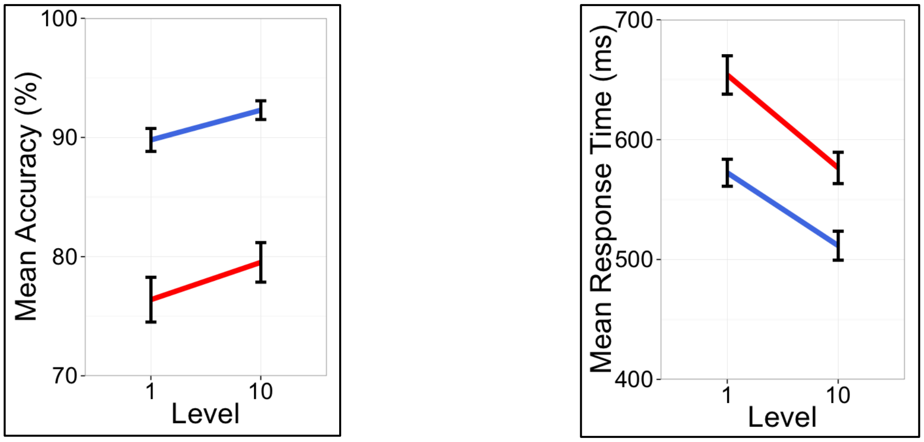

Figure 6 | Short-term improvement in Experiment 1. Child (red) accuracy qualitatively improved (non sig: $p > .2$), and adult (blue) accuracy significantly improved ($p < .05$). Child and adult response times significantly decreased ($p < .001$) across the test session.

Child accuracy qualitatively improved by 2.8% $t(114.26) = 1.25$, $p > 0.2$, and adult accuracy significantly improved by 2.5% $t(113.42) = 2.01$, $p < .05$ (see Table 2). Child response time significantly decreased by 76.01 ms $t(110.97) = 3.65$, $p < .001$, and adult response times significantly decreased by 60.82 ms $t(117.44) = 3.69$, $p < .001$ (see Table 3). Of note, average child group response time (576.3 ms) during level 10 was not significantly different from the adult group average response time (572.4 ms) in level 1 $t(114.21) = 0.23$, $p > .8$.

Table 2. | Short-Term Improvement in Experiment 1: Accuracy.

	Short-Term Improvement in Experiment 1			
Age	Level 1	Level 10	Difference (%)	*p*-value
Child	76.69	79.52	2.83	*ns*
Adult	89.79	92.29	2.5	<.05

Table 3. | Short-Term Improvement in Experiment 1: Response Time.

	Short-Term Improvement in Experiment 1			
Age	Level 1	Level 10	Difference (ms)	*p*-value
Child	652.47	576.39	76.08	< .001
Adult	572.37	511.55	60.83	< .001

Similar to the observed developmental transition in the previous section, we also saw an age-related transition in the amount of learning from level 1 to level 10 in terms of accuracy (see Figure 7). Older children cluster around average adult performance in both response times and accuracy. Post-hoc t-tests showed intermediately aged children ages 9 $t(9.91) = 0.84$, $p > .3$, and 12, $t(9.69) = 1.23$, $p > .2$ qualitatively improved the most in terms in accuracy from level to level 10. Children at age 9 significantly improved the most in terms of response times by 163.76 ms, $t(8.11) = 4.36$, $p < .01$, and improved significantly more than adults, $t(6.9) = 2.89$, $p < .05$. Children at age 10 also significantly improved by 136.98 ms, $t(11.68) = 3.1$, $p < .01$.

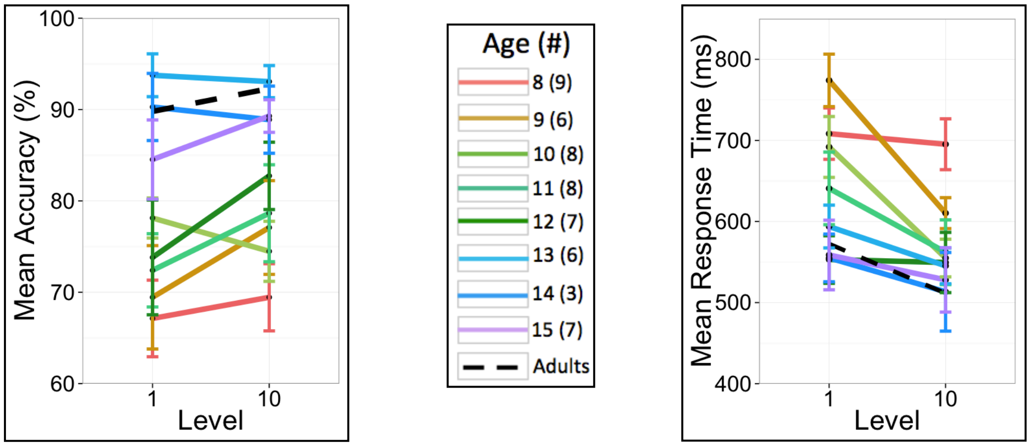

Figure 7 | Transition in Short-Term Learning in Experiment 1. Older children (ages 12, 14, and 15 years) performed similar to adults in both response times and accuracy. Intermediately aged children (ages 9 and 10) most significantly improved their response time performance from level 1 to 10 (*p's* < .01). Children ages 9 and 12 improved the most in terms of accuracy within the session (*p's* > .3).

Chapter 7: Experiment 2

HIGHER WORKING MEMORY DEMAND SIGNIFICANTLY AFFECTS PERFORMANCE IN ADULTS AND CHILDREN

Accuracy

The task accuracy regression revealed main effects of age, $F(1,91) = 83.82$, $p < .0001$, level, $F(9,3617) = 160.64$, $p < .0001$, and task-switching, $F(1,3617) = 8.97$, $p < .01$. As in Experiment 1, there were no significant differences between congruency conditions overall, $F(2,91) = 1.21$, $p > .3$, or within the age groups (Age x Congruency), $F(2,89) = 45.26$, $p > .8$. All results reported in this chapter are thus collapsed across the congruency condition groups.

Overall, children were less accurate (M =72.26, SD =18.18) than adults (M = 89.35, SD = 11.65), $t(699.99) = 16.22$, $p < .0001$. There was a significant interaction between age and level, $F(9, 3564) = 19.04$, $p < .0001$, where child and adult performance declined dramatically in levels with four response choices (levels 7, 8 and 9). Children's accuracy significantly differed between the two and four response choice levels by 24.7% (M = 80.69, SD = 9.54 at two choice levels, M = 55.95, SD =15.82, at four choice levels) $t(75.54) = 9.18$, $p < .0001$. Adult accuracy was also significantly different between the response number conditions by about 13.1% (M = 93.9, SD = 5.59, in two choice levels, M = 80.76, SD = 12.7 in four choice levels) $t(64.57) = 6.56$, $p < .0001$ (see Figure 8).

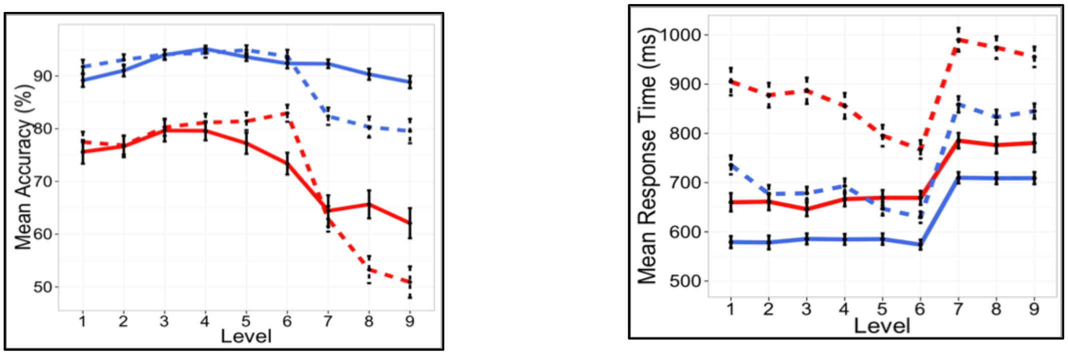

Figure 8 | Overall performance in Experiment 2. Performance across levels in children (red) and adults (blue) in Experiment 1 (solid lines) and Experiment 2 (dashed lines). Response time and accuracy had significant interactions between age and level ($p < .0001$); both age groups showed accuracy loss at the later four response choice levels.

Though there was a significant main effect of task switching, but there were no age effects, $F(1,3578) = 1.86$, $p > .1$. Switch trials were marginally more difficult relative to repeat trials; the average switch cost in accuracy for young adults was 1.1%, and 1.8% for children (see Figure 9). Additionally, there was no significant interaction between task switching and level manipulations for accuracy, $F(9,3578) = 1.81$, $p > .06$.

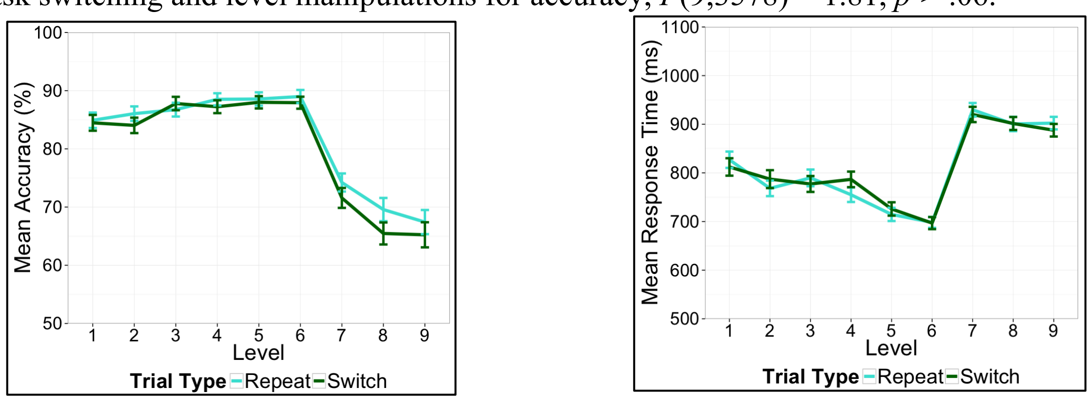

Figure 9 | Overall task-switching performance in Experiment 2. In Experiment 2 there were no significant interactions between age and task switching ($p > .1$), level and task switching ($p > .06$), for accuracy and response time. Further, there was no significant interaction between age, task switching, and level ($p > .8$) in terms of accuracy

Overall, participants were significantly less accurate $t(1751.5) = 2.28$, $p < .03$, in Experiment 2 compared to Experiment 1. Adults, but not children, performed significantly worse in Experiment 2, t(655.9632 = 3.97, $p < .0001$. Additionally, overall differences between repeat and switch trials (switch costs) were significantly greater than in Experiment 1 than in Experiment 2 for accuracy $t(1883.7) = 2.44$, $p < .02$. There were no age effects (p's $> .07$). Experiment 2 produced a significantly larger effect of the response choice number (2 vs. 4) manipulation on accuracy in adults, $t(63.23) = 7.08$, $p < .0001$, and children, $t(101.48) = 4.81$, $p < .0001$.

Response Times

The response time regression revealed main effects of age, $F(9,4581) = 45.26$, $p < .0001$ and level, $F(9,3595) = 162.86$, $p < .0001$. Surprisingly, there was no main effect of task switching, $F(1,3595) = .46$, $p > .4$. There were no significant differences between congruency conditions, $F(2,91) = .39$, $p > .6$, or their interaction with age (Age x Congruency) $F(2,89) = .22$, $p > .7$.

There was a significant interaction between age and level $F(9,3565) = 5.89$, $p < .0001$; children were consistently slower than young adults throughout the game. Child response times significantly differed between the two and four response choice levels by 151.08 ms (M = 824.72, SD = 146.26, at two choice levels, M = 975.8, SD = 134.46, at four choice levels) $t(91.36) = 5.21$, $p < .0001$. Relative to the low demand study (Experiment 1), adults were more susceptible to the response number manipulation in later levels with four response choices. Adult response times were significantly different between the response number conditions by 180.93 ms (M = 663.19, SD = 89.02, in two choice levels, M = 844.12, SD= 103.31, in four choice levels), $t(91.99) = 9.19$, $p < .0001$ (see Figure 8).

Qualitatively, overall response times were slightly slower in switch trials (M= 809.92, SD = 182.89) relative to repeat trials (M=808.7, SD = 179.15). A two-way interaction between task-switching and level manipulations for response times was non-significant, $F(9,3491) = 1.17$, $p > .3$ (See Figure). Notably, there was no significant interaction between age, task switching, and level, $F(9,3491) = .45$, $p > .9$, for response times; adults and children showed the same pattern of task-switch costs throughout the session .

In comparison to Experiment 1, overall performance was significantly slower in Experiment 2, $t(1469.47) = 21.23$, $p < .0001$. In terms of age group performance, both children, $t(737.25) = 18.46$, $p < .0001$, and adults, $t(794.23) = 14.33$, $p < .0001$, were significantly slower in overall (levels 1-9) in Experiment 2. There were no significant overall differences between repeat and switch trials between Experiment 1 and in Experiment 2 for response time, $t(1588.81) = 1.36$, $p > .1$. Adults in Experiment 2 were more significantly more susceptible to the response choice number manipulation, $t(77.78) = 3.69$, $p < 0.001$; children did not show a significant difference between the two studies, $t(96.47) = 0.89$, $p > .3$.

TRANSITION TO ADULT-LIKE PERFORMANCE LEVELS OBSERVED AT 14 YEARS

Following the same procedure as in Experiment 1, we binned the child age group by chronological age-year to explore performance changes from ages 8 to 15 years. Post-hoc paired t-tests showed beginning at the age of 14 children show adult-like levels of accuracy (P-value by age year: 13: $p < .0001$, 14: $p > .5$, 15: $p > .05$), especially during later levels. Children ages 14 and 15 years also performed significantly better than their younger peers $t(59.2) = 7.6$, $p < .0001$ (see Figure 10).

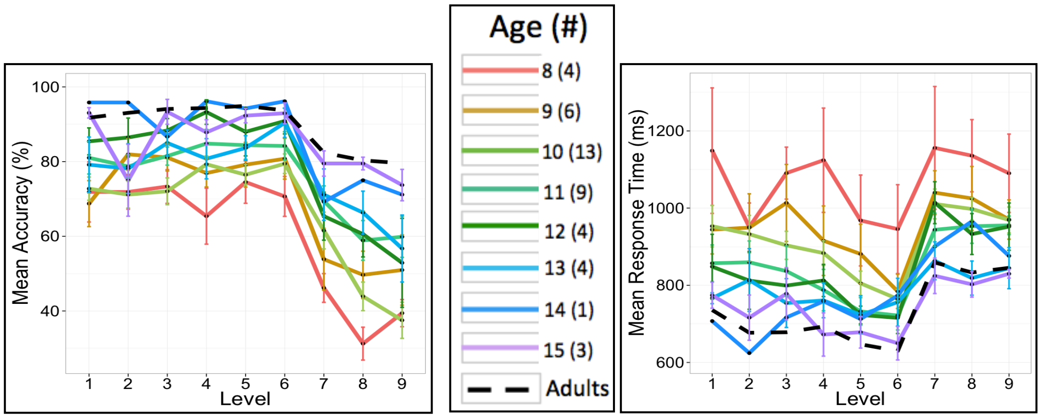

Figure 10 | Age Transition in Experiment 2. Post-hoc t-tests revealed a transition to adult levels of response time around the age of 14 years ($p > .2$). Children ages 14-15 performed significantly better than younger participants ($p < .0001$) in both response time and accuracy and demonstrated more adult-like patterns of performance.

We observed a trend toward faster response times in older children. Children ages 14 and 15 were significantly faster than the younger children $t(60.26) = 7.96$, $p < .0001$, and not significantly different from adults in later levels (P-value by age year: 13: $p < .01$,14: $p > .2$, 15: $p > .4$).

Temporary Learning Within task

Overall, 84 of the 95 participants (87% children; 89% adults) improved in response time and 62 (68% children; 62% adults) improved in terms of accuracy. As in Experiment 1, additional post hoc t-tests were conducted to investigate learning from the first level to an identical level (with novel stimuli) at the end of the study (level 10). Both children and young adults improved their performance over the course of the experiment (approximately 45 minutes) (see Figure 11).

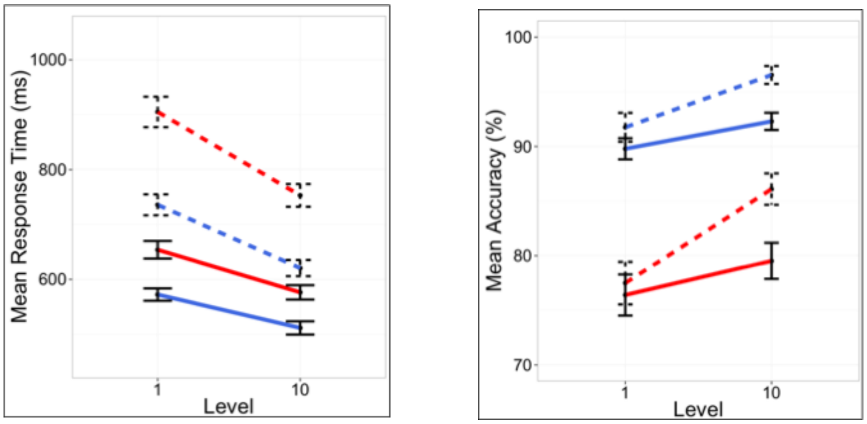

Figure 11 | Short-Term Learning in Experiment 2. Child and adult accuracy significantly improved ($p < .01$), and response times significantly decreased ($p < .0001$). Child and adult performance in the high demand study improved more relative to the low demand study (response time, $p < .02$ for each group) (Child accuracy, $p < .02$; Adult accuracy, $p > .1$). Child response times at level 10 closely matched initial adult response times at level 1 (*ns*: $p > .5$) in both Experiment 1 and Experiment 2.

Child accuracy improved significantly by 8.5%, $t(84.45) = 3.5$, $p < 0.001$, and adult accuracy improved significantly by 4.7%, $t(78.53) = 3.08$, $p < .01$ (see Table 3). Child response time significantly decreased by 152 ms, $t(85.07) = 4.39$, $p < .0001$, and adult response times significantly decreased by 115 ms $t(88.29) = 4.78$, $p < .0001$ (see Table 4). Similar to the pattern observed in Experiment 1, child group average response time during level 10 was not significantly different from the adult group average response time (753.07 vs. 735.85 ms) during level 1, $t(92.23) = 0.61$, $p > .5$. Importantly, child performance in the high demand study improved significantly more relative to the low demand study (child accuracy, $p < .02$; adult accuracy, $p > .1$) and both children and adults significantly improved in terms of response time (child response time, $p < .01$; adult response time, $p < .02$).

Table 3. | Short-Term Improvement in Experiment 2: Accuracy.

	Short-Term Improvement in Experiment 2			
Age	Level 1	Level 10	Difference (%)	*p*-value
Child	77.48	86.08	8.6	< .001
Adult	91.75	96.52	4.77	< .01

Table 4. | Short-Term Improvement in Experiment 2: Response Time.

	Short-Term Improvement in Experiment 2			
Age	Level 1	Level 10	Difference (ms)	*p*-value
Child	905.11	753.07	152.04	< .0001
Adult	735.85	620.62	115.23	< .0001

Similar to the observed developmental transition in the previous section, we also saw an age transition in the amount of learning from level 1 to level 10 in terms of accuracy (see Figure 12).

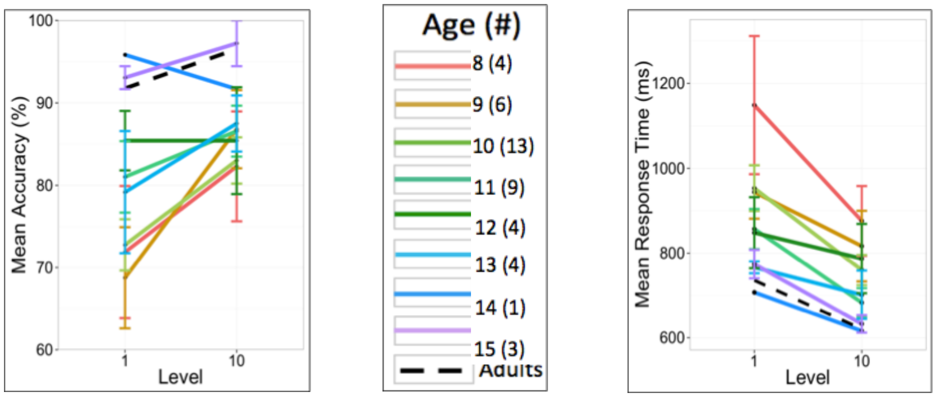

Figure 12 | Age-Related Transition in Short-Term Learning in Experiment 2. Older children (ages 14 and 15) improved similarly to average young adult performance in both response time and accuracy (response time and accuracy, p >.06). Intermediately aged children (9, 10 and 11 years) improved the most relative to their peers in the child age group.

In terms of accuracy, intermediately aged children ages 9, $t(9.39) = 2.32$, $p < .05$, and 10, $t(23.75) = 2.44$, $p < .03$, improved significantly (18.06 and 10.26%, respectively) from the first level of the experiment to the final level 10.

Post-hoc paired t-test comparisons showed intermediately aged children ages 10, $t(20.79) = 2.99$, $p < .007$, and 11 , $t(14.55) = 2.98$, $p < .01$, significantly improved the most in terms of response time performance (193.09 and 174.04 ms, respectively) from level 1 to the last level 10 in the experiment session. Due to a fewer number participants, 8-year-olds qualitatively improved the most by 272.85 ms, yet the post-hot test did not reach significance $t(4.44) = 0.36$, $p > .2$.

Discussion

General Discussion

We designed two novel tasks to compare stability of task-switching abilities across children and adults with four goals in mind. The nine level switching task consisted of several manipulations including differing number of response choices (2 and 4), number of cued tasks (2, 3 and 4), and response choice consistency. First, we aimed to find which manipulations would most affect child and adult performance within the task. Second, we wanted to test if there were developmental transitions in task-switching performance within the child age group. Third, we aimed to test for short-term learning within a test session. Fourth, we investigated how working memory load interacts with task-switching performance over age.

In both tasks, children were consistently slower and less accurate than adults. Further, the higher working memory demand in Experiment 2 led to lower performance levels in both age groups relative to Experiment 1. There were clear developmental transitions in performance related to the task-switch manipulations in our sample of children at age 12 in Experiment 1 and later, at age 14 in Experiment 2. Finally, we found significantly greater short-term performance improvement in Experiment 2. In both Experiment 1 and Experiment 2, child response times at the end of the session were similar to starting adult performance. As a whole, these results reveal consistent differences in task switching performance between age groups, but also relative short-term flexibility within a given individual.

Adults Consistently Performed Significantly Better in Both Experiments

As expected, young adults consistently performed better than children, especially in more challenging levels. However, the strikingly parallel pattern in performance in response time in both studies was unexpected. The gradual decrease in response times with age in the child group observed in later task levels suggests differential cognitive processing over age [Kirkham, Cruess, & Diamond, 2003].

Previous work has established that both child and adult performance are susceptible to task switch-costs, additional task demands and increased working memory load [Kray & Lindenberger, 2001; Koch et al., 2010; Gade & Koch, 2007; Diamond, 2013; Bunge et al., 2002]. With respect to our first goal, attempts to reduce differences in adult and child performance through task-switching manipulations were largely unsuccessful; children were slower, less accurate, and more affected by the task-level manipulations than adults. However, in both Experiment 1 and Experiment 2, we were able to scaffold child performance in the last level (level 10) to match that of adults in the first level of the experiment.

By comparing the results of both Experiments, the higher working memory demand in Experiment 2 more significantly impacted task-switching performance in both age groups, especially in later levels. Further, switching costs varied with cognitive load; switch costs were significant in Experiment 1, but not Experiment 2. We believe this may be a result of the overall greater baseline difficulty in Experiment 2, relative to Experiment 1. Participants must remember the cued task rule and response choice and then repeat that process iteratively in all following trials. Therefore it may be the case that in Experiment 2, repeat and switch trials required a similar degree of cognitive processing.

CRITICAL TRANSITION IN CHILD PERFORMANCE LATER IN HIGHER COGNITIVE DEMAND TASK

The transition period from child-like to adult-like levels of accuracy found around 12 years in our sample within the low demand task (Experiment 1) is consistent with a similar performance shift due to pubertal changes found in previous literature [Cepeda et al., 2001; Crone et al., 2004]. However, in the second high demand task (Experiment 2), we saw a similar transition to adult-like performance but later, at age 14. We interpret these results to mean a transition to more adult-like patterns of performance is neither a process rooted solely in task-switching ability, nor a gradual accumulation of skill as a function of numerical age alone [Wendelken et al., 2011].

Instead, this shift will clearly result from a combination of biological, social, and environmental factors influencing the development of cognitive control as well as effortful self-regulation [Deak et al., 2004; Rueda, Posner & Rothbart, 2005; Kochanska & Aksan, 2006; Posner et al., 2007; Kochanska & Knaack, 2000; Rothbart, 1994]. Importantly, these results suggest basic foundations of cognitive flexibility (e.g. inhibitory control, task-switching) may be developed, but what seems to improve across adolescence is cognitive processing capacity [Swanson, 2004], which supports working memory capacity.

SIGNIFICANTLY MORE SHORT TERM LEARNING AND IMPROVEMENT IN TASK PERFORMANCE WITH HIGHER WORKING MEMORY DEMAND

Within the experiment sessions, adult performance significantly improved in both response times and accuracy, and children improved in response times. These improvements substantiate the ability to temporarily train and improve task-switching abilities in children within a single session.

Added working memory demands in Experiment 2 promoted significantly more short-term improvement, especially in children. The improvement observed in the high demand task may be driven by added challenge and interest relative to the easier task. In both studies child performance (response times) in the last level was comparable to adult performance in the first level, emphasizing working memory, sustained attention and cognitive flexibility can be improved upon with practice [Morrison & Chein, 2011; Capa et al., 2012].

This supports the results from the current studies indicating children and adults may perform differently, but both age groups have potential to improve cognitive flexibility. For instance, in Experiment 1, children at age 9 improved more than any other age including the adult group. In Experiment 2, children at age 9 and 10 improved more than their peers. This suggests intermediately developed adaptive control systems may have the most potential to improve.

While we make no claim as to lasting effects of the improvement observed in our sample, several other studies have demonstrated cognitive training has the potential to produce executive functioning, working memory and attention improvement in children [e.g. Rueda, Posner & Rothbart, 2005; Diamond & Lee, 2011]. We are currently pursuing a line of research aimed to test the generalizability of performance improvement seen in this task.

LIMITATIONS

It is important to acknowledge limitations in both studies. Experiment 1 is not without memory demand; there is a minimal amount of working memory required. Experiment 2 was designed to increase working memory and cognitive load demands relative to Experiment 1, but also changes the amount of visual information available onscreen for the participants, thus confounding memory effects. As noted earlier, we cannot generalize the short-term learning effect observed within the testing session to improved cognitive functioning outside of the experiment session. Further, we did not test children or adults in a follow up session to test task switching or executive function, though it is a productive future direction. Finally, we had minimal measures about our participants more generally (IQ, subclinical features, personality measures, etc.), which is a goal for future research.

CONCLUSION

Age-related improvements in response times were gradual, but a shift in accuracy was observed around age 12 years in the low demand study and around age 14 years in the high demand study. We saw similar rates of short-term performance improvement in both age groups and more improvement with greater working memory demand (Experiment 2). We hypothesize the added challenge in the higher cognitive load condition (Experiment 2) promoted a higher rate of learning because it required additional engagement, increased interest, and anecdotally, was more entertaining for both adults and children. Increasing working memory demand affected accuracy only at the hardest levels, while response times were slower at all levels for both ages. With practice, child response times were similar to initial adult response times in the low and high demand studies.

FUTURE DIRECTIONS

For future studies of cognitive control development, we plan to collect neuropsychological and personality measures in order to investigate individual differences as well as possible correlations task-switching development may have with personality and other factors. Another interesting future direction for this study would be to incorporate multimodal data collection. Collecting functional brain data, eye-tracking data, sleep habits, and personality measures, as well as genetic samples would yield a richer dataset able to examine factors relating to the development of executive function and control in childhood and adolescence.

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